Mobile Haptic Interaction with Extended Real or Virtual Environments

Norbert Nitzsche Uwe D. Hanebeck Günther Schmidt

Institute of Automatic Control Engineering
Technische Universität München, 80290 München, Germany
E-mail: Norbert.Nitzsche@ei.tum.de

Abstract

A novel mobile interface for physical interaction with extended real or virtual environments is presented, which frees the operator from being bound to a stationary kinesthetic work station. As a result the operator's unrestricted natural walking is now available as input to the locomotion control of the teleoperator or the avatar. Hence, the operator is enabled to use proprioceptive perception of locomotion, which is a basic requirement for navigation and wayfinding.

To allow unrestricted locomotion in the local environment, the first new idea is to have the haptic interface, which is neccessary for physical interaction, move along with the operator. This could be achieved by using a portable kinesthetic interface, which, however, is not capable of displaying large external forces.

Hence, the second new idea is to use a mobile haptic interface, which actively follows the operator's locomotion. The corresponding locomotion platform is continuously positioned in such a way that maximum manipulability is guaranteed. In order to accomplish this under the kinematic and dynamic restrictions of the wheel-based platform, the operator's intention of locomotion is predicted.

A prototype telepresence system for kinesthetic exploration of extended virtual environments has been designed according to the proposed paradigm, implemented, and tested.

1 Introduction

The purpose of telepresence systems is to create the impression of being present in an environment not directly accessible by a human operator. Such an environment can be real or virtual and will be referred to as remote environment in the sequel.

This paper shows how the workspace of force-reflecting telepresence systems can be extended by realistic locomotion. The resulting extended-workspace telepresence system leads to increased immersiveness by allowing simultaneous haptic interaction and locomotion.

Current haptic interfaces are mostly stationary and limited to workspaces similar to that of the human arm [1, 2]. This results in two severe restrictions regarding applicability: (1) The operator is immobile. (2) The workspace in the remote environment is limited.

The second restriction can easily be removed by shifting the workspace in the remote environment. With today's force-reflecting teleoperation systems, however, the locomotion of the proxy (teleoperator or avatar) necessary for workspace relocation is commanded by abstract locomotion interfaces like mouse, joystick or reindexing [2]. Abstract locomotion interfaces do not provide proprioceptive, i.e., kinesthetic and vestibular, feedback of locomotion. For that reason the operator does not get the desired impression of moving through the remote environment but rather feels the remote environment moving relative to himself.

An enhancement of the sensation of presence could be achieved by allowing the operator unrestricted locomotion relative to the remote environment in order to extend his workspace.

Interfaces for realistic, unrestricted telepresent locomotion already exist in the field of virtual reality. They provide interactive visual exploration, but no force-feedback [3]. With these locomotion interfaces the operator not only uses visual but also kinesthetic and vestibular perception of locomotion. The class of realistic locomotion interfaces includes omnidirectional treadmills [4, 5], programable foot platforms [6] and setups for tracking free locomotion of the operator in the local environment [7, 8].

Tracking the operator's locomotion and performing a corresponding locomotion in the remote environment is particularly suited as a locomotion interface for haptic interaction in extended workspaces. Unrestricted locomotion in the local environment, however,

IEEE International Worksop on Robot
and Human Interactive Communication
0-7803-7222-0/01/$10.00©2001 IEEE

conflicts with immobility of the operator as required by stationary haptic interfaces. This conflict is resolved by moving the haptic display along with the operator. As a result, force-reflecting telepresence is now possible in workspaces much larger than before, Table 1.

		Telepresent Locomotion	
		none or abstract	realistic
Manipulation/ Interaction	no force-feedback	• computer games • remote control • CAD-systems	• interactive visual exploration in VR
	force-feedback	• computer games • master/ slave-teleoperation	• extended-workspace haptic interaction

Table 1: Classification of current telepresence systems and the novel telepresence systems for extended workspaces (shown in gray).

The following section will discuss basic principles of kinesthetic interfaces, which do not lead to immobility of the operator. In Sec. 3 a detailed description of the proposed approach is given, which is based on a mobile haptic interface. In Sec. 4 a first implementation is presented together with experimental results.

2 Approaches for Extended–Workspace Interfaces

To permit unrestricted locomotion while interacting with remote environments, a haptic interface must be available at every point of the workspace of a free walking human operator.

An obvious approach are portable kinesthetic interfaces attached to the operator. Such systems have already been implemented especially as finger kinesthetic displays but also for arm kinesthetics [9, 10]. Given today's actuator technology, portable kinesthetic interfaces, however, are subject to weight determined force limitations. Furthermore, they are not capable of realistically displaying large external forces due to the lack of an external base. In [11] grounded haptic feedback was found superior to ungrounded haptic feedback in wall detection and distance estimation experiments.

Employing stationary manipulators with large workspaces as kinesthetic interfaces is not a satisfactory solution because material expenses and stiffness problems would grow rapidly with workspace size. In addition, coherent workspaces free from internal collisions could only be realized by high-redundancy manipulators.

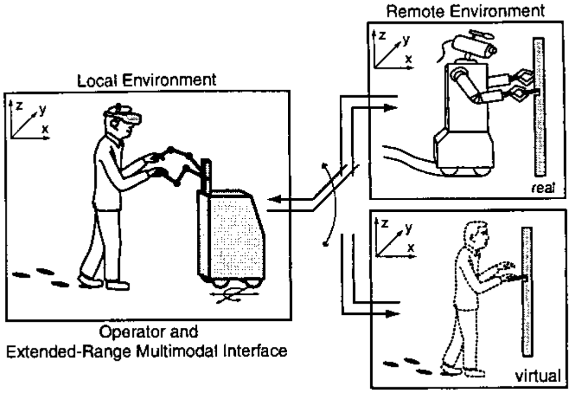

Figure 1: Mobile haptic interface for interaction with extended remote environments.

The new idea presented in this paper is to use a mobile haptic interface actively following the operators locomotion, Fig. 1. The workspace of such an interface is only limited by the size of the available floor space. Furthermore, mobile haptic interfaces pose less restrictions regarding force magnitude and display of external forces compared to portable devices.

3 Mobile Haptic Interface - Setup and Requirements

The implementation of a mobile haptic interface (MHI) can benefit from the available knowledge in the field of mobile manipulation. An MHI will comprise a mobile, e.g. wheel-based, platform and a manipulator with end-effectors appropriate for haptic display. The total system is kinematically redundant with the individual degrees of freedom differing in their dynamic properties.

In this application, the platform has to comply with two partly contradictory requirements. On the one hand it has to provide the necessary kinematics and dynamics to be able to follow the operator's locomotion with sufficient accuracy. Hence, the platform must be omnidirectional and of low inertia. On the other hand, a certain weight is required to transmit the forces and torques excerted on the MHI by the operator into the ground.

The manipulators of the MHI are in contact with the operator's hands via end-effectors and provide force-reflecting interaction with the interface and the telepresence system. The workspace of these manipulators should be large enough to cover the workspace of the human arms. Thus the mobile platform with its greater inertia does not have to follow the movements of the operator's hand.

In order to guarantee the operator's natural freedom of motion, the MHI has to follow the operator's locomotion and must be positioned optimally in terms of manipulability. For that purpose the relative position and orientation of platform and operator have to be determined. In addition, the absolute spatial arrangement of either platform or operator is necessary to perform locomotion in the remote environment corresponding to the operator's locomotion.

Due to kinematic and dynamic restrictions of the platform, optimal manipulability can only be achieved by a predictive behavior of the mobile interface. Hence, manipulability is optimized not only instantaneously but over a certain time horizon by predicting future spatial arrangement of the operator on the basis of suitable dynamic models.

4 First Prototype: walkii

4.1 Implementation Issues

For evaluation of the methods essential for meeting the requirements stated in the preceeding section, a first prototype setup, which is illustrated in Fig. 2, was implemented. With this extended-workspace Human-System-Interface, called walkii -wide area locomotion and kinesthetic interaction interface, one-fingered kinesthetic exploration is possible in a virtual environment of about 3 m by 3 m floor space.

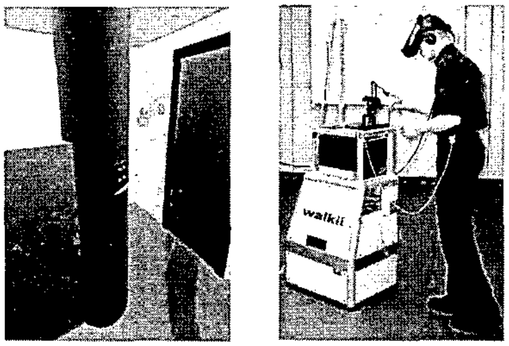

Figure 2: First prototype of the novel multi-modal mobile haptic interface: walkii - wide area locomotion and kinesthetic interaction interface. The operator is exploring a square room of about 3 m by 3 m floor space.

The operator can freely walk around in the workspace and perceives an equivalent change of position and orientation in the virtual environment. Visual stereoscopic feedback is provided by an HMD (Head Mounted Display). Forces resulting from contact with objects in the virtual environment are displayed at the operator's finger tip by the novel mobile haptic interface.

The mobile haptic interface combines a mobile, omnidirectional robot platform [12] and the commercially available haptic interface PHANToM Premium 1.0.

To determine the position and orientation of the operator a magnetic tracking-system is used with one sensor on the head and one sensor at the hip. The magnetic tracker is also used for platform localization. All six degrees of freedom of the head position and orientation are used as input for rendering the stereoscopic view. The hip sensor provides information about the current position and orientation of the operator.

A configuration optimization algorithm uses that information together with the current PHANToM configuration to generate the reference input for the MHI position controller. Hence, the platform actively follows the operator's body and hand movements and provides maximum manipulability of the manipulator. As a result, the operator does not collide with any workspace boundaries of the PHANToM and is free to use a work space as large as the available floor space.

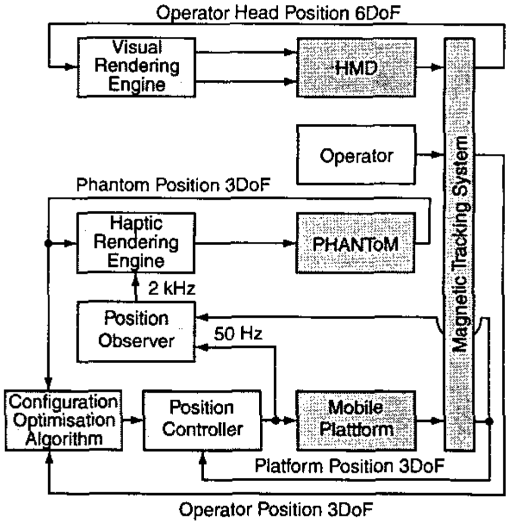

Figure 3: walkii - hard- und software components.

For computation of the forces resulting from one–fingered exploration of virtual environments a haptic rendering library for simple virtual environments with geometrical primitives was developed and used. Based on that library it is possible to run the haptic rendering loop at 2 kHz on an Intel Pentium II with 450 Mhz for a world comprising 50 surfaces .

Since localization of the platform can only be performed with sampling frequencies far below the requirements for haptic rendering, an observer for estimating the spatial arrangement of the MHI is employed. The observer provides position and orientation data synchronously with the haptic rendering loop.

Figure 3 gives an overview on the hard- and software components of the extended workspace multimodal telepresence system.

4.2 Experimental Results

For purposes of demonstrating the functionality of the novel mobile haptic interface and for comparing it to current sytems and approaches, the following shape recognition experiment was developed and executed as a benchmark test.

Six virtual prismatic objects are created, whose cross-sections are illustrated in Fig. 4. The edges of all cross-sections are parallel to the x- or y-axes or tilted by an angle of 45°. The corners of all cross-sections are grid points of a 0.3 m by 0.3 m rectangular grid. All prisms are standing perpendicular to the ground. The prisms are classified into three groups I, II, III according to the complexity of their cross-sections, Fig. 4.

The task of the test person is to haptically explore the shape of the virtual prisms, without any visual feedback from the virtual world, and to subsequently sketch the cross-section of the prismatic test object as perceived. Before the experiment, the test person is told the geometrical restrictions regarding shape and size as stated above. The test person is asked to stop exploration when being confident to know the shape of the test object.

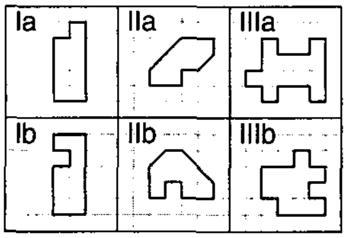

Figure 4: Cross-sections of prismatic test objects used for shape recognition experiments.

Task completion time and recognition accuracy are used as a measure for task performance and usability of the MHI. Recognition accuracy is evaluated by comparing six selected features of the virtual cross-section to the cross-section sketched by the subject with regard to shape and size. Thus, recognition accuracy is scored on a scale from 0 to 6.

Figure 5 shows, as an example, a typical motion sequence of a test person and the mobile haptic interface during exploration of the virtual prism Ib. The fingertip closely follows the contour of the test object whereas the path of the mobile platform is determined by both finger and trunk position of the operator. The operator is enabled to walk all around the object, which indeed is the natural way of haptically exploring the shape of this type of objects.

The eight subjects taking part in the experiment are devided into two groups. Group A are displayed the prisms Ia, IIa and IIIa, whereas group B explore prisms Ib, IIb and IIIb. Exploration is performed with the novel mobile haptic interface in all tests. The cross-section sketches of two of the subjects are exemplarily displayed in Fig. 6.

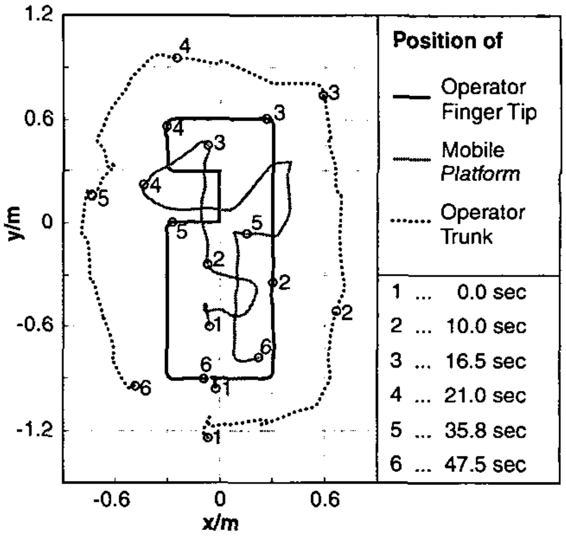

Figure 5: Experimental results: A test person (operator) haptically explores the virtual prismatic test object Ib (top view). The numbered dots on the graphs indicate corresponding points in time.

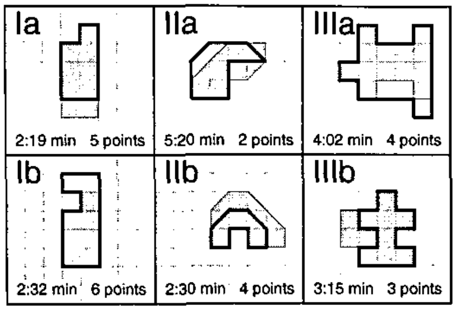

Figure 6: Mobile Haptic Exploration: Cross-sections of test objects as perceived by test persons. The gray areas indicate the true shape of the virtual prism. Completion time and recognition accuracy (on a scale from 0 to 6) are given beneath each figure and resemble typical values.

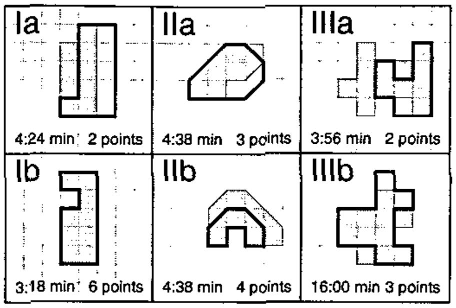

Figure 7: Desktop Haptic Exploration: Cross-sections of test objects as perceived by test persons. The gray areas indicate the true shape of the virtual prism. Completion time and recognition accuracy (on a scale from 0 to 6) are given beneath each figure and resemble typical values.

4.3 Comparision with Current Systems

After subjects have completed the shape recognition test with the mobile haptic interface they perform the test on another three test objects with a desktop haptic interface, again without visual feedback. The desktop haptic interface also employs a PHANToM 3DoF device for one-fingered haptic exploration. The other hand is used to move the virtual test object relative to the exploring hand by means of an ordinary computer mouse.

Group A perform this second test on objects Ib, IIb and IIIb, whereas group B are displayed objects Ia, IIa and IIIa. The cross-sections drawn by the same subjects as in Fig. 6 are displayed in Fig. 7.

The results of the two shape recognition experiments - mobile haptic interface and desktop haptic interface - are summarized in Table 2. The values given for completion time and accuracy score are average values of four subjects each.

For all six objects, task completion time with the mobile haptic interface is only 30 - 80 % of the task completion time observed in the desktop haptic interface experiments. Task completion time, in this experiment, is the time used by the test person until confident to know the shape of the test object. Hence, shorter task completion time does not necessarily mean that the task is easier to complete with mobile haptics. Rather, it is interpreted as an indicator for subjects feeling more comfortable and confident. This interpretation complies with the statements of subjects who almost without exception claim to have problems integrating and memorizing movements of the virtual object when using the desktop setup. In some cases subjects lost the test object several times which also is a result of the just mentioned path integration and memorization problem.

In the case of test objects from group I and III the results with regard to recognition accuracy support the conclusion drawn from the task completion time results. Subjects obtain higher accuracy scores in less

	Mobile	Desktop	
Ia	2:04	4:34	min
	3.7	3.0	points
Ib	2:35	4:04	min
	4.5	3.3	points
IIa	3:04	5:13	min
	2.7	4.0	points
IIb	3:18	5:02	min
	4.5	4.7	points
IIIa	4:14	5:03	min
	3.7	3.0	points
IIIb	4:11	13:22	min
	4.3	2.0	points

Table 2: Comparison of mobile haptic exploration and desktop haptic exploration: Results of a large-scale shape recognition experiment. The table shows average task completion time in minutes and a score representing recognition accuracy.

time on those objects. On objects of group II, however, subjects achieve higher accuracy scores with the desktop haptic device. This is mainly because cross-sections of group II objects do not only consist of edges parallel to x- and y-axes but also edges with an angle of 45°. Hence, shape recognition involves determining corner angles and distinguishing between 45°, 90° and 135° corners. Due to a certain degree of non-smoothness still noticeable in the movements of the mobile haptic interface, corner angle estimation is not as easy as it is with a stationary device. This problem will be solved in the future by employing more effective configuration optimization algorithms and position control strategies.

5 Conclusion

A novel mobile telepresence interface was proposed, which enables simultaneous haptic interaction and realistic locomotion in real and virtual environments. This new quality is a fundamental step towards higher degrees of immersiveness.

Abandoning the requirement for immobility of the operator permits a particularly simple and realistic realization of the locomotion interface compared to treadmills and programmable foot platforms. The comparatively high effort for implementing a mobile haptic interface can be reduced by exploitation of the vast knowledge in the field of mobile manipulators. It is even possible to make use of existing hardware.

The presented experimental setup impressively demonstrates that proprioceptive perception of locomotion combined with haptic feedback can substantially support the completion of large-scale object recognition tasks in a remote environment, which require the utilization of natural navigation skills. Yet, the results also indicate future research directions for improving the usability of mobile haptic interfaces.

Acknowledgments

This work was supported in part by the German Research Foundation (DFG) within the Collaborative Research Centre SFB 453 on "High-Fidelity Telepresence and Teleaction".

References

[1] V. Hayward, "Survey of Haptic Interface Research at McGill University". *Proceedings of the Workshop on Advances in Interactive Multimodal Telepresence Systems*, pp. 91–98, München, Germany, 2001.

[2] J. M. Hollerbach, "Some Current Issus in Haptics Research". *Proceedings of the IEEE International Conference on Robotics & Automation*, pp. 757–762, San Francisco, California, 2000.

[3] R. P. Darken, "Spatial Orientation and Wayfinding in Large-Scale Virtual Spaces II". *Presence*, Vol. 8, Dec. 1999.

[4] H. Iwata, "Walking About Virtual Environments on an Infinite floor". *Proceedings of the Virtual Reality Conference*, pp. 286–293, Houston, Texas, 1999.

[5] R. P. Darken, W. R. Cockayne, D. Carmein, "The omni-directional treadmill: A locomotion device for virtual worlds". *Proceedings of the ACM UIST*, pp. 213–222, 1997.

[6] http:// www.sarcos.com / interpic_virtualinter.-html.

[7] H. Baier, F. Freyberger, G. Schmidt, "Interaktives Stereo-Telesehen - Ein Baustein wirklichkeitsnaher Telepräsenz". *at Automatisierungstechnik*, July 2001.

[8] C. Cruz-Neira, D. Sandin, T. A. DeFanti, "Surround-screen projection-based virtual reality: The design and implementation of the CAVE". *Proceedings of the ACM SIGGRAPH*, pp. 135–142, 1993.

[9] C. S. Tzafestas, P. Coiffet, "Dextrous Haptic Interaction with Virtual Environments: Hand-Distributed Kinesthetic Feedback and Haptic Perception". *Proceedings of the IARP First International Workshop on Humanoid and Human Friendly Robotics*, pp. 286–293, Tsukuba, Japan, 1998.

[10] G. C. Burdea, *Force and Touch Feedback for Virtual Reality.* John Wiley & Sons, New York, 1996.

[11] C. Richard, M. R. Cutkosky, "Contact force perception with an ungrounded haptic interface". *Proceedings of the ASME IMECE 6th Annual Symposium on Haptic Interfaces*, pp. 15–21, Dallas, Texas, 1997.

[12] U. D. Hanebeck, N. Šaldic, "A Modular Wheel System for Mobile Robot Applications". *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 17–23, Kjongju, Korea, 1999.